Pilot Injector Redesign to reduce N+3 Cycle Emissions for a Gas-Turbine Combustor

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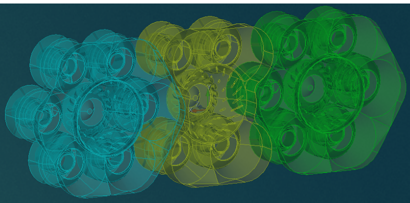
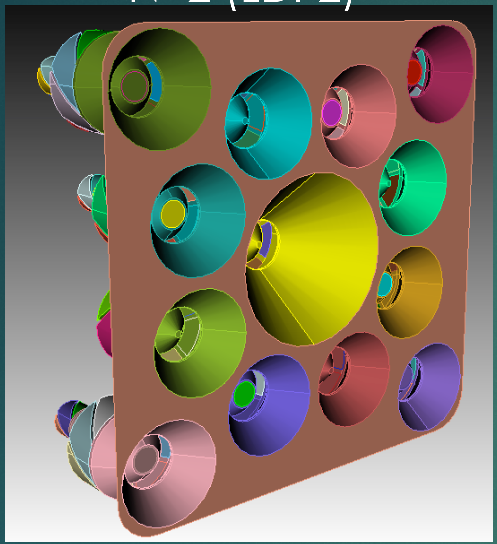
Motivation for Current Work

- NASA's N+3 (2025-2035 target) Project Goals:
  - Reduce NOx emissions to 80% below ICAO CAEP6 standards under Advanced Air-Transport Technology (AATT) NASA project
  - "smaller core-size" and "higher OPR" as compared to N+2/ERA
- NASA Glenn Research Center's N+3 Project Focus:
  - Design/Evaluate Lean-Burn/Lean-Dome combustors in partnership with OEMs and injector manufacturers to meet program goals
- Current work: CFD analysis of a *redesigned* 3rd generation Lean Direct Injection (LDI) flame-tube array for medium-power N+3 ICAO conditions using National Combustion Code (OpenNCC)

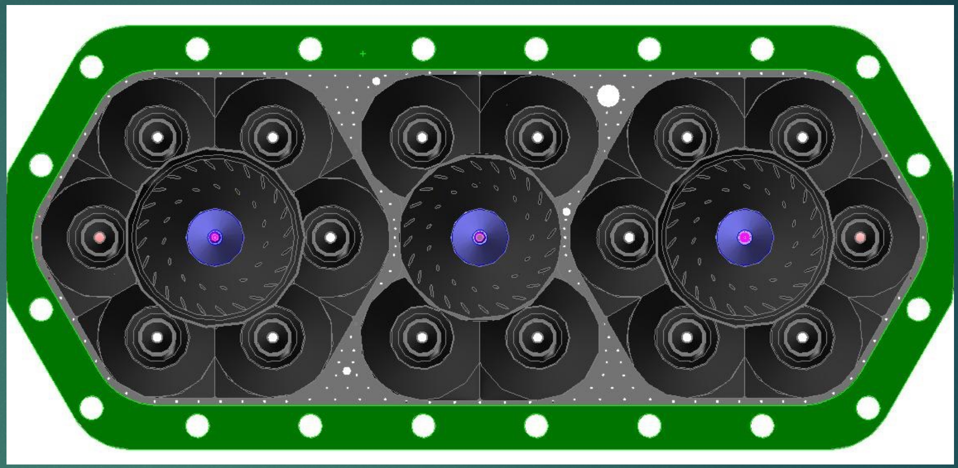
N+2 (LDI-2) vs N+3 (LDI-3) Injector Layout



N+2 (LDI-2)



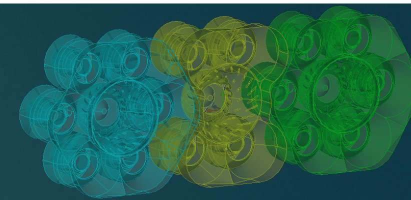
N+3 (LDI-3)

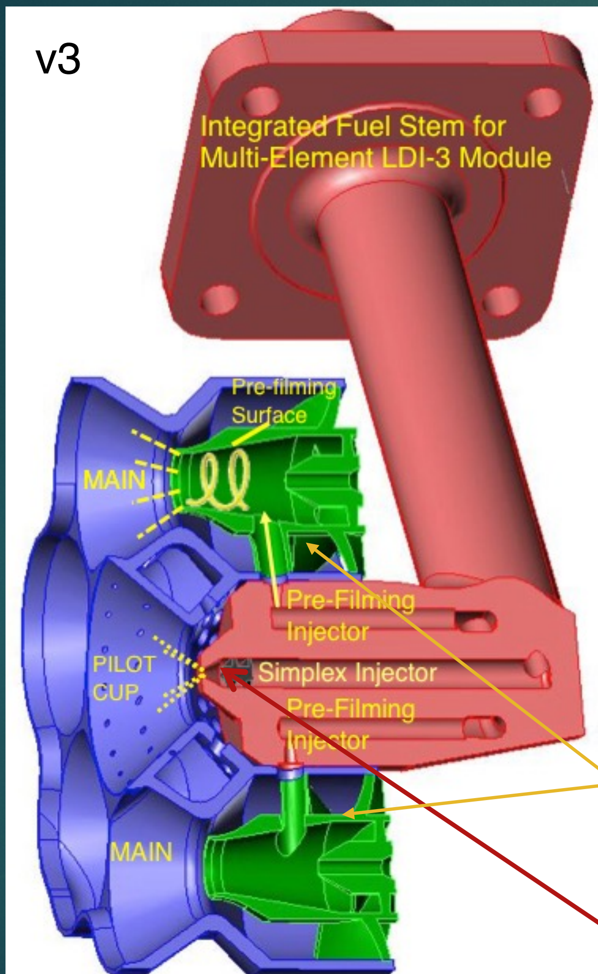


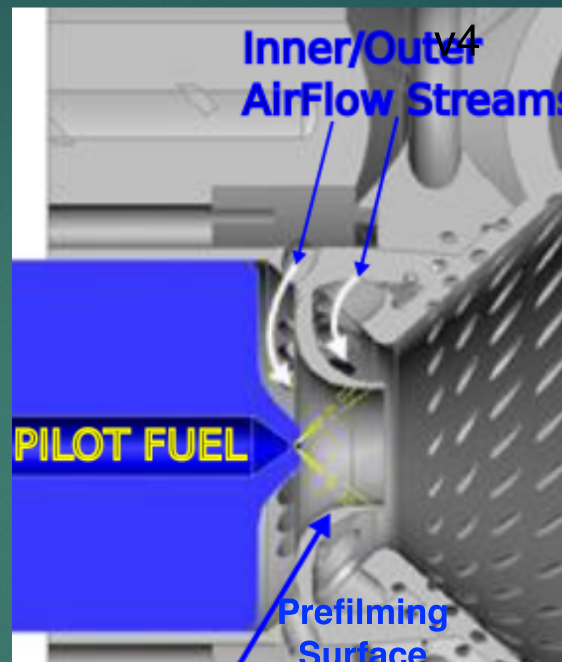
- To accommodate requirements of N+3 combustor designs:
  - Reduce dome height >> denser packaging of injectors at dome face
  - Maintain similar effective area >> higher reference velocity
  - Redesign of Main element fuel injection: plain orifice, pre-filming injector
  - Redesign of Pilot element air-flow passages: compound-angle plain-jets

  - Reduction in fuel-system complexity, better thermal management of fuel >> integration of multiple fuel lines into single fuel stem

LDI-3 Pilot/Main Injector Design





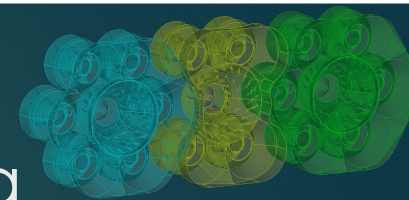


- *Pilot* fueled by simplex injector spraying onto pre-filming surface
  - CFD used to down-select inner/outer airflow stream flow-rates
  - CFD used to decide on relative swirl orientation of airflow streams (co-rotating or counter-rotating)

Woodward FST pre-filming injector for *Mains*.
- Fuel injected via plain jet orifice into prefilmer.
- Axial bladed swirlers for air flow

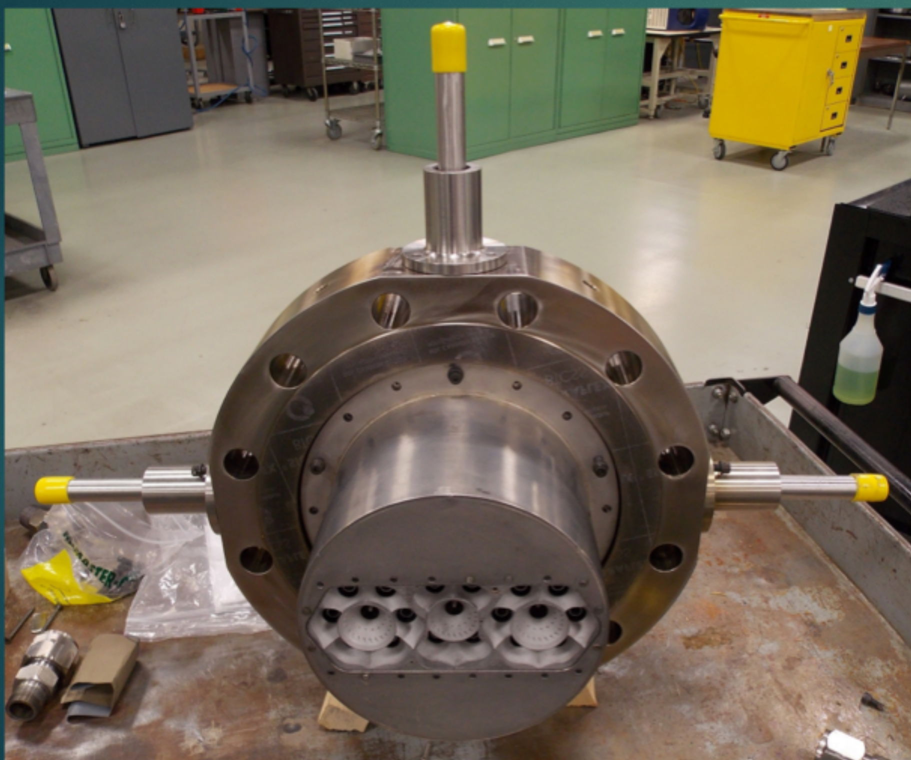
Pilot fueled by simplex injector. Circumferential air-flow

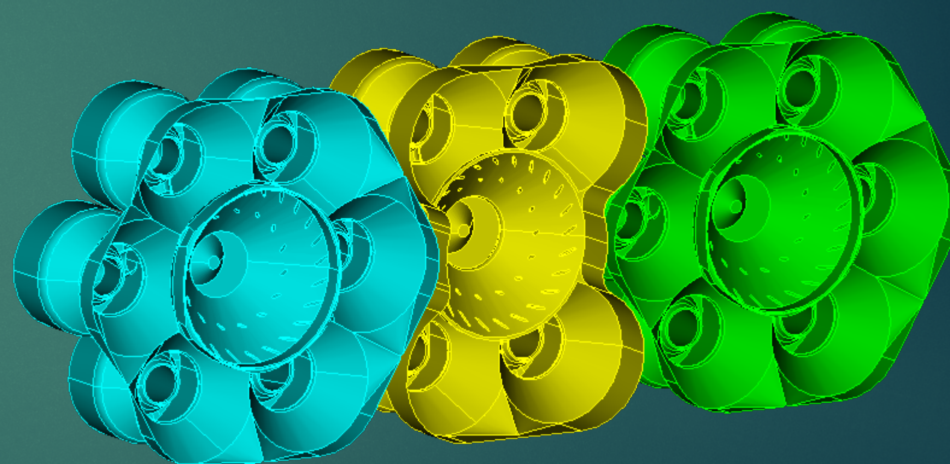
OpenNCC analysis provided design-optimization of main/pilot element airflow passages



19-Element Module Assembly Flametube Setup for NASA GRC's CE-5 Rig

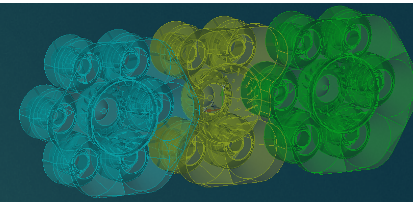
Aft looking Upstream





Aft Looking Upstream

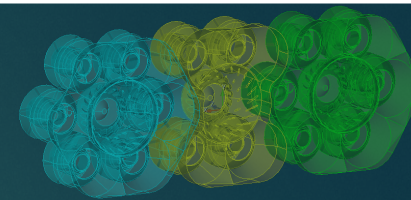
Version 4 vs Version 3 PILOT



The goal was to arrive at an improved Pilot injector configuration that would meet the design requirements of :
- similar effective area when compared to version 3 design
- ‘optimal’ size of primary recirculation zones for flame stability
- emissions improvements at cruise conditions

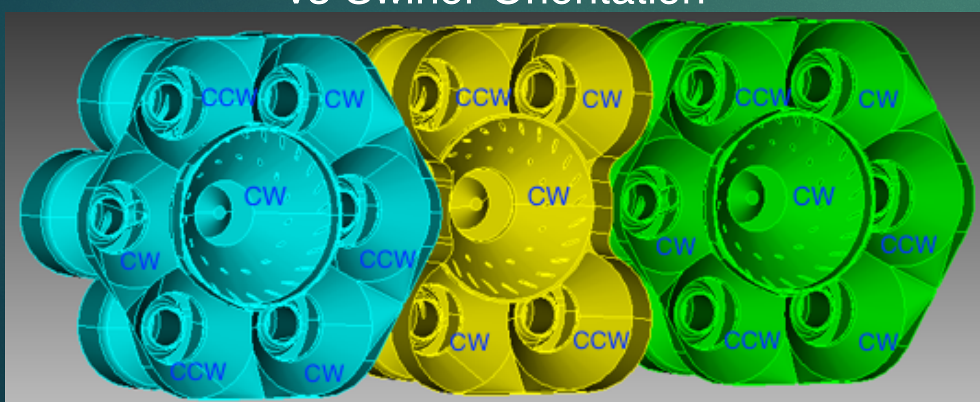
Geometry parameters studied with OpenNCC in the current effort included
- air-flow splits of primary and secondary air-streams of pre-filming Pilot
- orientation (counter or co-rotating) of the pre-filming pilot injector primary and secondary air-streams

Version 4 vs Version 3 Pilot Injector



- Partially pre-filming Pilot (v4) vs non pre-filming Pilot (v3)
- All Mains co-Rotating (v4) vs co-/counter-rotating Mains (v3)
- Cooling flow in the pre-filming pilot injector venturi (v4) was increased by 35% as compared to the 'baseline' pilot (v3). Cooling flow area at the dome was increased by 10%.

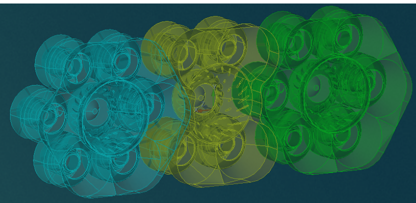
v3 Swirler Orientation

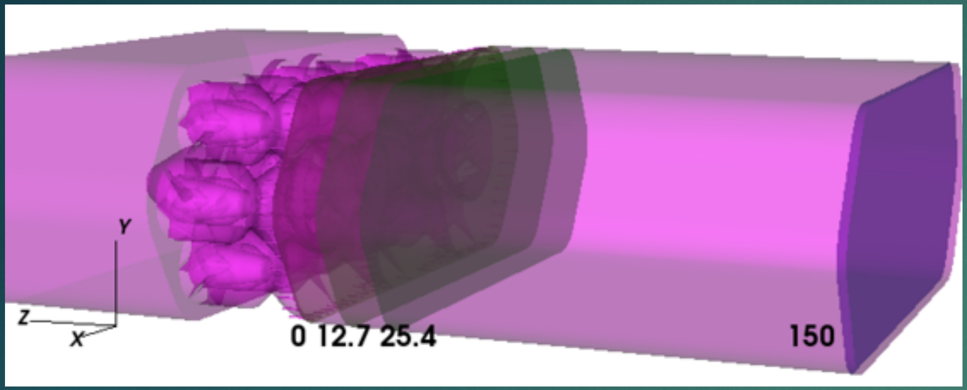


v4 Swirler Orientation

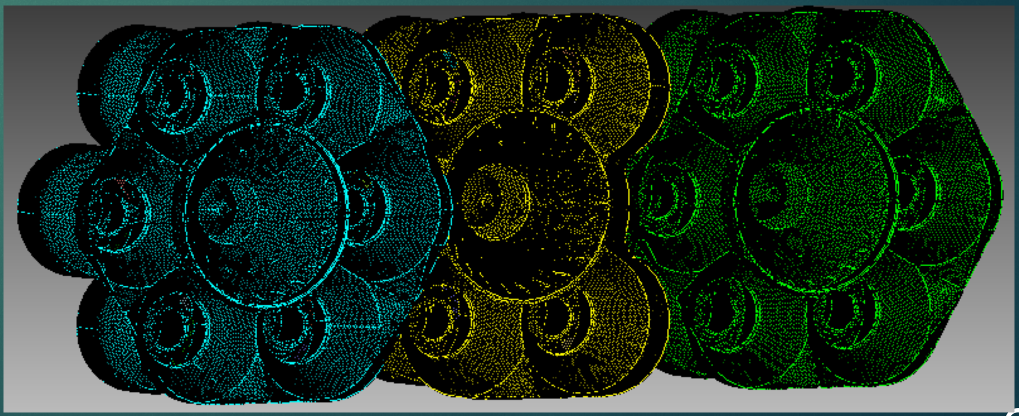
OpenNCC CFD provided design inputs for Pilot element airflows, cooling passage design

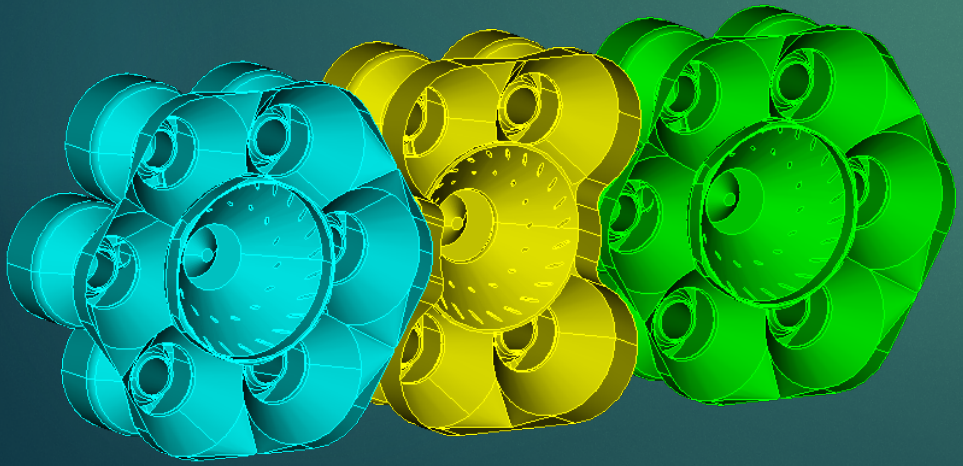
CFD Setup for 3-Cup Flametube (Computational Domain, Mesh)





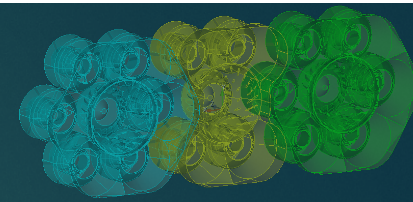
Surface Mesh





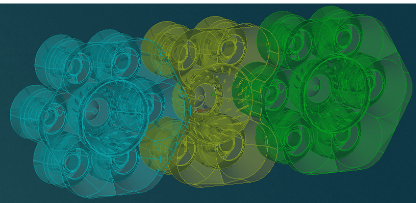
Aft Looking Upstream

Physical Models for OpenNCC CFD



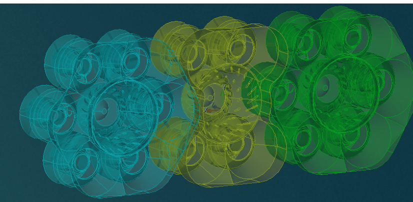
- Finite volume, , 4-stage Runge-Kutta explicit scheme, 2nd order time-accurate
- Time-Filtered Navier-Stokes (TFNS) solver (Liu, Wey AIAA 2014-3569)
- Two-equation, cubic k-ε model with variable Cμ and dynamic wall functions with pressure gradient effects (Shih, NASA TM 2000-209936)
- Reduced-kinetics, finite-rate chemistry. Jet-A fuel modeled as surrogate mixture of decane (73%), benzene(18%), hexane(9%) (14 species, 18 steps)(Kundu, AIAA Paper 2014-3662)
- Lagrangian spray-modeling for liquid fuel droplets (prescribed droplet distribution, injection velocity and direction) (Raju, NASA CR-2012-217294)
- Turbulence-chemistry interaction modeling: Joint Scalar Monte-Carlo PDF solver (Raju, AIAA Paper 2004-0327)

Non-Reacting Flow OpenNCC CFD



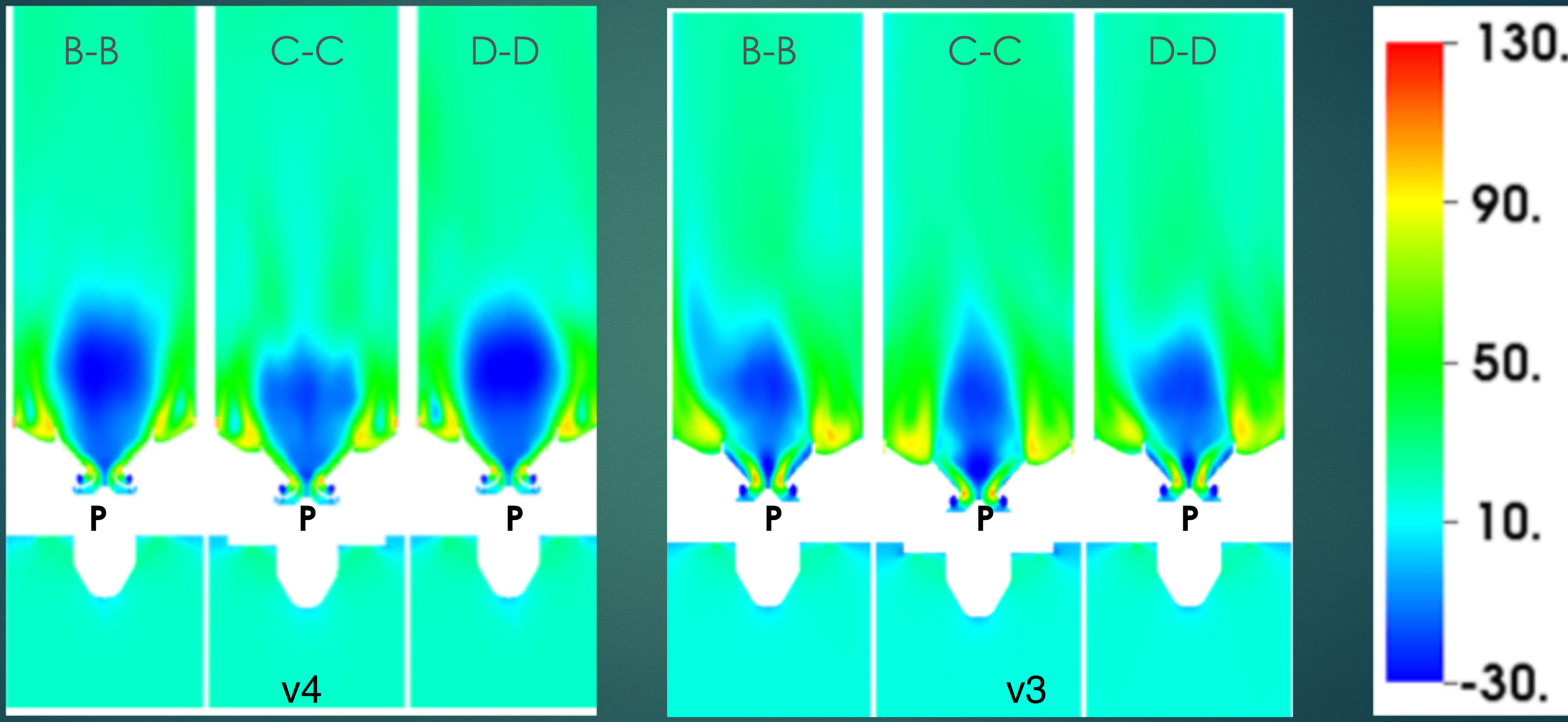
- Use OpenNCC CFD analysis to evaluate aerodynamics characteristics, effective-area of flametube
  - What are the flow-field differences between the ‘baseline’ (v3) pilot injector and the redesigned (v4) pilot injector (w/partial pre-filming)
  - What are the effective-area (ACd) differences between co-swirling and counter-swirling air-streams for redesigned pilot (v4)?
  - How well does the redesigned pilot (v4) maintain the effective area (ACd) as compared to the ‘baseline’ design

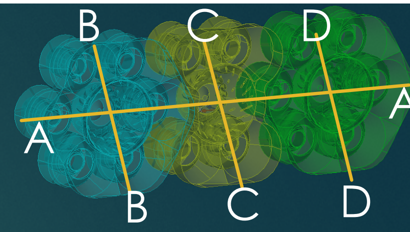
CFD Step 1: Non-Reacting TFNS



- P3=130psi, T3=811K, Dp = 3%
- Fix Ptot, Ttot at Inflow; Fix pressure at Outflow
- Obtain converged RANS solution. Run TFNS (time-accurate) for 20m-s.
- Compute ACd from CFD prediction of mass flow rate at each inflow boundary. *Use same pressure-drop value (P3*Dp) for each inflow boundary.*
    - aggregate of 16 mains
    - each pilot-primary, each pilot-secondary
    - four row aggregate cooling for each pilot venturi
    - dome-face cooling (aggregate)
    - auxiliary cooling (aggregate for each cup)

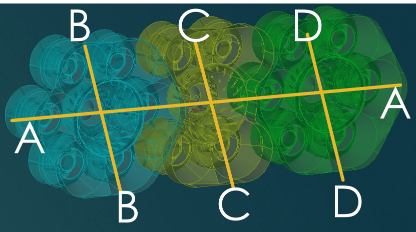
Non-Reacting Flow - Axial Velocity(m/s) Pilot Centerline: v4 vs v3

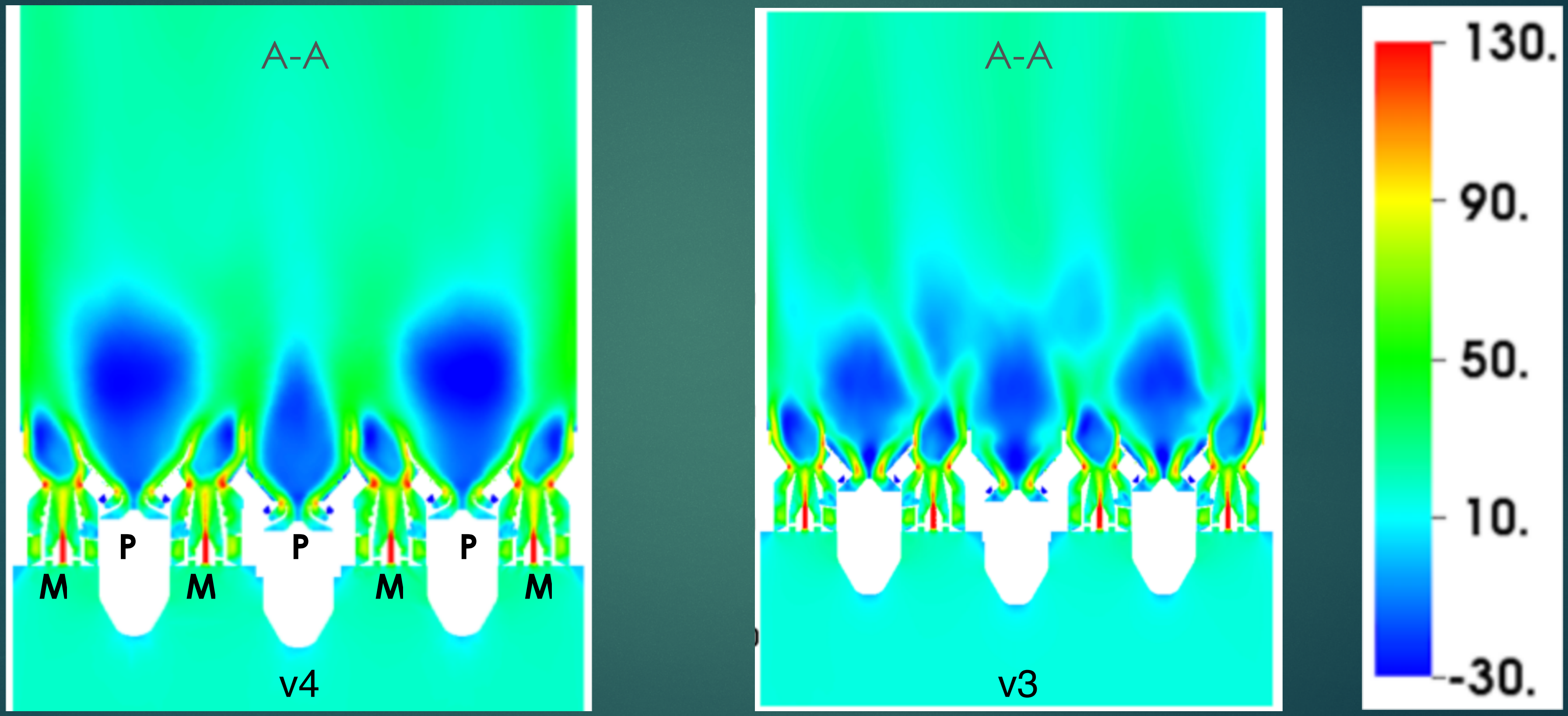




Pilots for v4 show much larger CTRZ as compared to those for v3

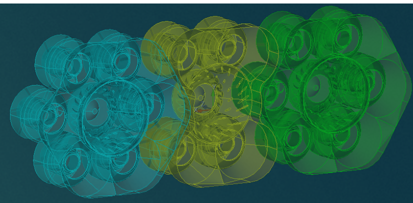
Non-Reacting Flow - Axial Velocity(m/s) Flametube Centerline: v4 vs v3





Pilots for v4 show much larger CTRZ as compared to those for v3

Effective Area Prediction - OpenNCC (v3,v4) vs Experiment



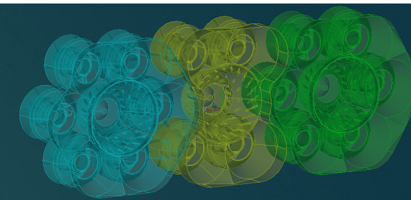
Components	Computed AC_d (in^2) (**v4**)	Computed AC_d (in^2) (**v3**)	Experiment AC_d (in^2) (**v3**)	% AC_d change **(v4 -v3)/v3**
Main Injectors (16)	2.413	2.4323	2.3613*	-0.8%
Pilot Injectors (3)	0.327	0.3348	0.3104	-2.3%
Pilot Cooling Holes (2 and 4 rows of holes per pilot for v3 and v4, respectively)	0.117	0.0433	*(included in Mains)	35%
Dome Face Cooling Holes	0.0456	0.0418	*(included in Mains)	9.1%
Total	**2.9026**	**2.8522**	**2.6717**	**1.8%**

OpenNCC prediction target is for total AC_d to be within 10% of experimental data

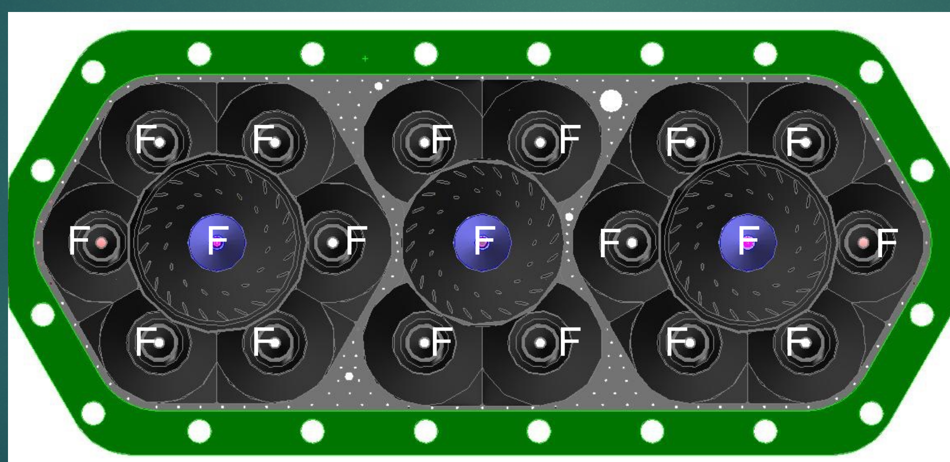
Step 2: Reacting-Flow OpenNCC

- Use OpenNCC CFD analysis to evaluate mixing, performance and emissions at medium power conditions
  - What are the flow-field differences between the ‘baseline’ (v3) pilot injector and the redesigned (v4) pilot injector (w/partial pre-filming)
  - What are the performance and emissions characteristics of the two flame tubes (v3 and v4)

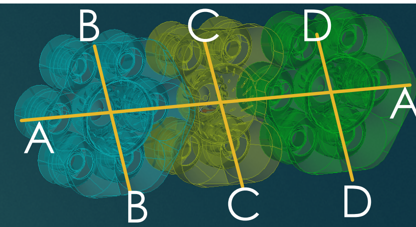
LDI-3 Cycle Condition for CST Cruise

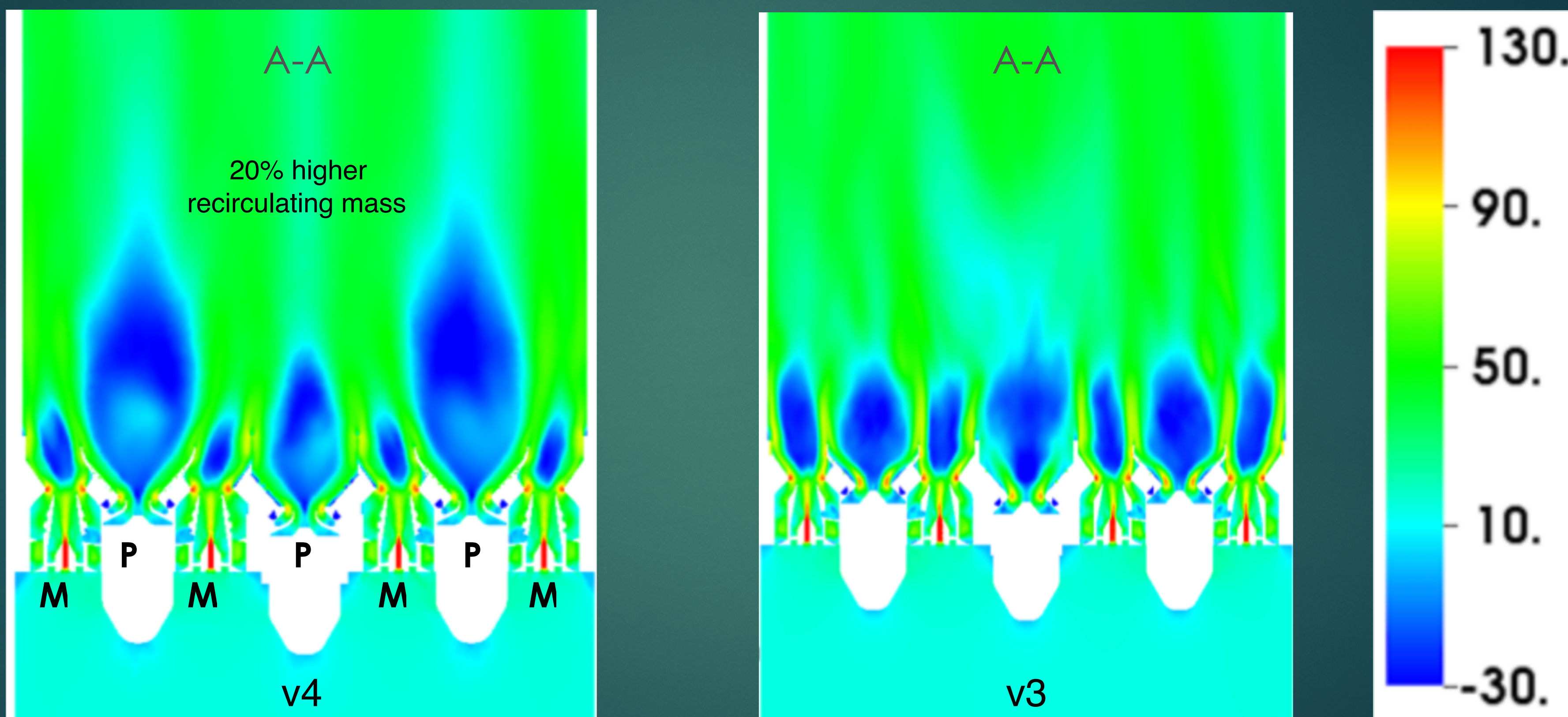


- All Pilots and Mains are fueled at the same equivalence ratio of 0.438 (Fuel/Air ratio = 0.03)
- P_3 = 0.896MPa, T_3 = 811K, **D**p = 3%, T_4 = 1785K



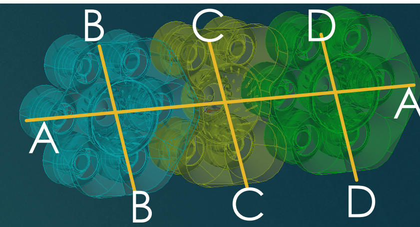
Reacting Flow - Axial Velocity(m/s) Flametube Centerline: v4 vs v3

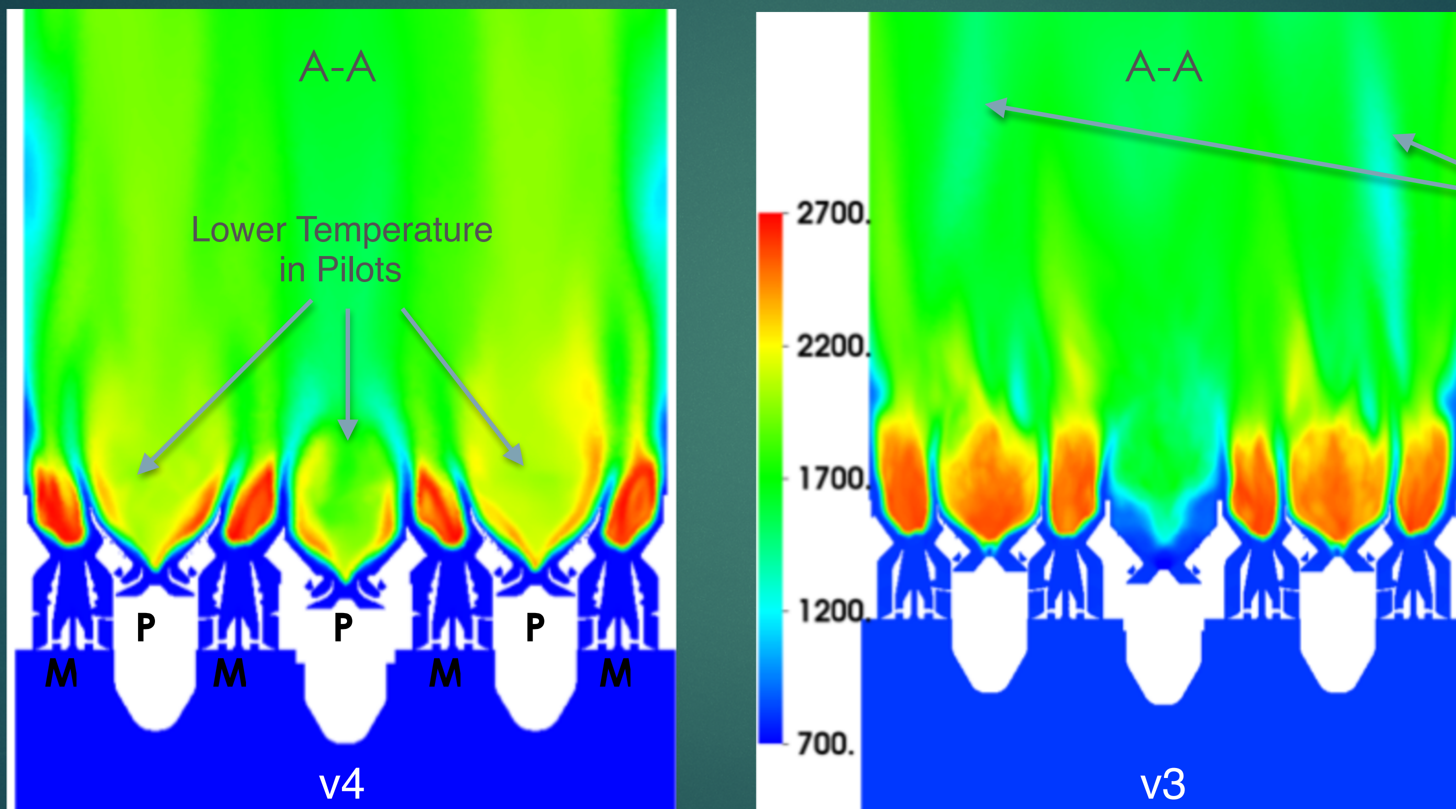




Pilots for v4 show much larger CTRZ as compared to those for v3

Reacting Flow - Temperature (K)
Flametube Centerline: v4 vs v3



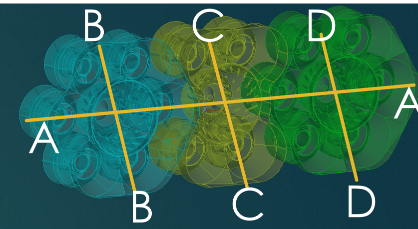


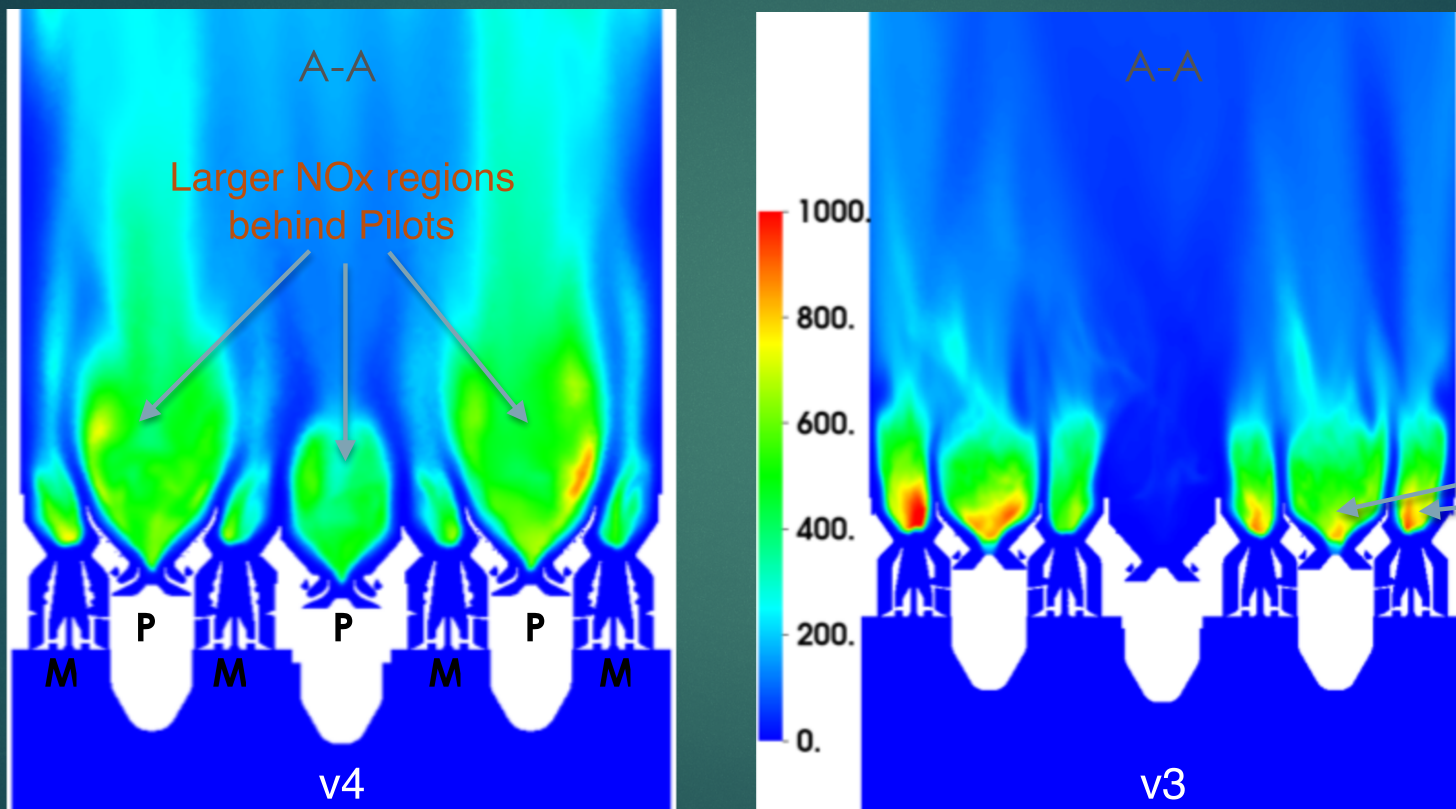
Cold Streaks extend far downstream

Exit Plane T_4 :
T_4 (CEA) = 1780K
T_4 (v4) = 1775K
T_4 (v3) = 1755K

Pilots for v4 show lower temperature flame zones near dome face
Much fewer ‘cold streaks’ observed in v4 configuration (better ‘pattern factor’)

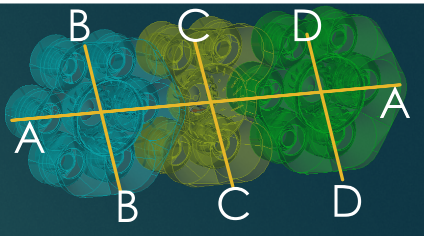
Reacting Flow - NO mass-fraction(*1e6) Flametube Centerline: v4 vs v3



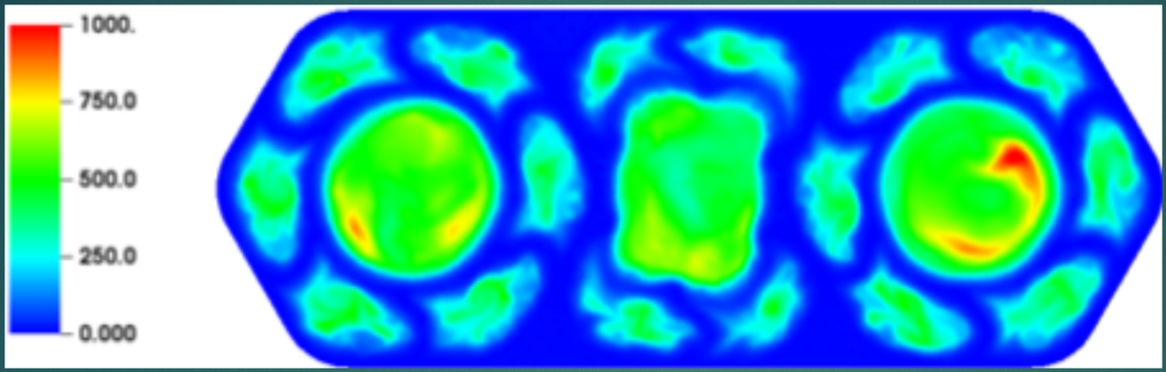


Pilots for v4 show much larger NOx production regions than v3
Peak values of NOx (Pilot AND Mains) are lower for v4

Reacting Flow - NO mass-fraction(*1e6) Combustor Dome Face: v4 vs v3



v4

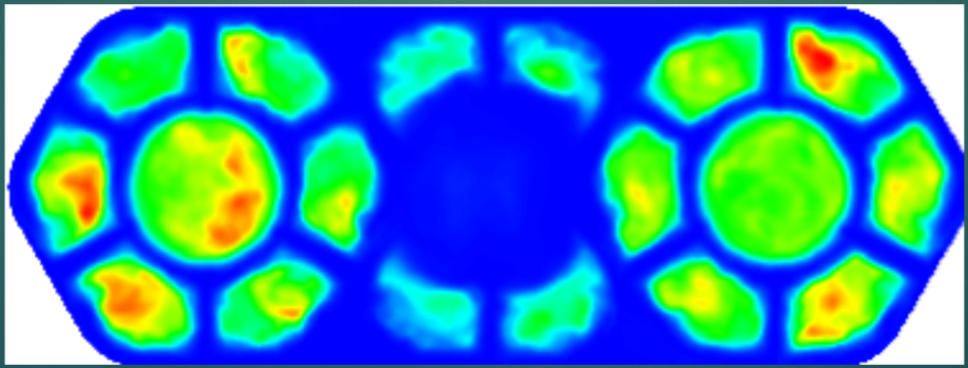


EINOx = 6.5

EINOx (Expt)[1] = 5.0

[1] Tacina et. al GT 2019-90484

v3



EINOx = 7.7*
(*with CFD correction for center Pilot)

EINOx (Expt)[2] = 6.1

[2] Tacina et. al ISABE 2017

CFD Prediction of lower EINOx for pre-filming Pilot (v4) matches experimental data trend

Summary and Future Work

- CFD analysis of a three-cup, 19-element LDI-3 flametube array performed with OpenNCC for two different Pilot Configurations
- EINOx predictions for the new pre-filming Pilot injector configuration are within 15% of measured experimental data (medium power)
- EINOx for the new-prefilming Pilot injector configuration is 20% lower than the original Pilot injector
- Future work will focus on improving the pre-filming Pilot design to further decrease EINOx. The current design (v4) will also be analyzed for LTO (idle, takeoff, approach) CST conditions.

Acknowledgements

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- VisIt flow visualization software (Lawrence Livermore National Labs)